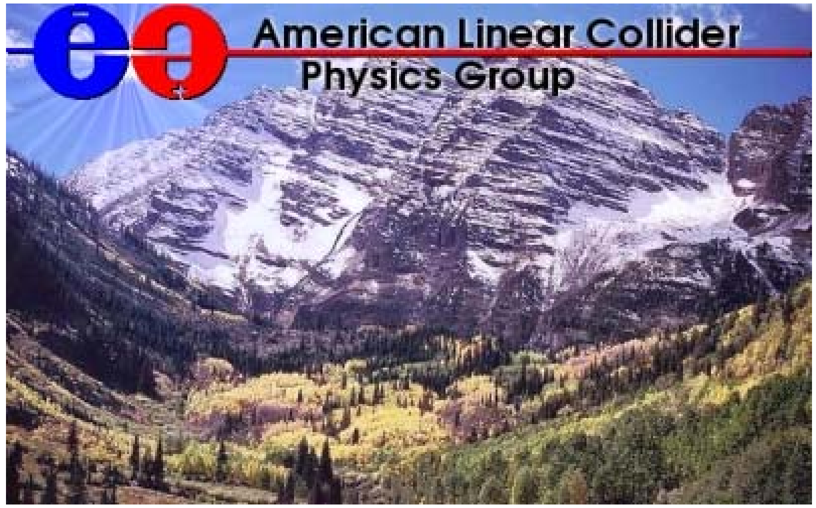


2005 International Linear Collider Physics and Detector Workshop
and Second ILC Accelerator Workshop
Snowmass, Colorado, August 14-27, 2005

Current Cryomodules and Changes for ILC

Carlo Pagani

INFN Milano and DESY

On leave from University of Milano

TESLA Cryomodule Design Rationales

- High Performance Cryomodule was central for the TESLA Mission
  - More then one order of magnitude was to be gained in term of capital and operational cost
- High filling factor: to maximize real estate gradient
  - Long sub-units with many cavities (and quad): cryomodules
  - Sub-units connected in longer strings
  - Cooling and return pipes integrated into the main cryomodule
- Low cost per meter: to be compatible with a long TeV Collider
  - Cryomodule used also for feeding and return pipes
  - Minimize the number of cold to warm connections for static losses
  - Minimize the use of special components and materials
  - Modular design using the simplest possible solution
- Easy to be alligned and stable: to fullfil beam requirements

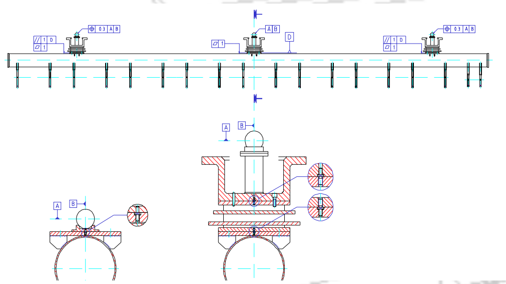
Performing Cryomodules

Three cryomodule generations to:

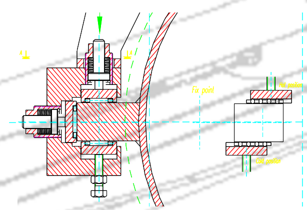
- improve simplicity and performances
- minimize costs

"Finger Welded" Shields

Reliable Alignment Strategy

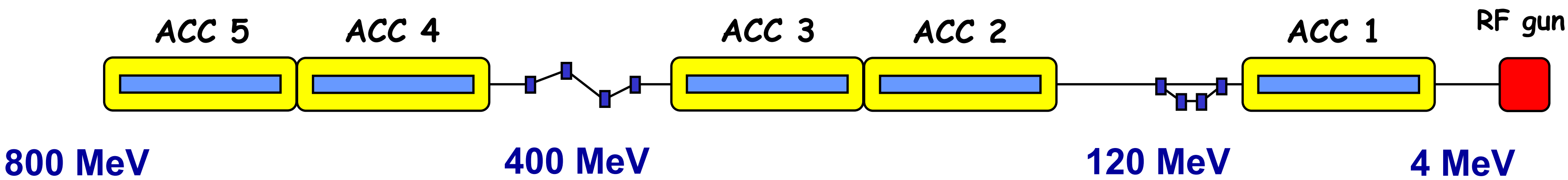


Sliding Fixtures @ 2 K

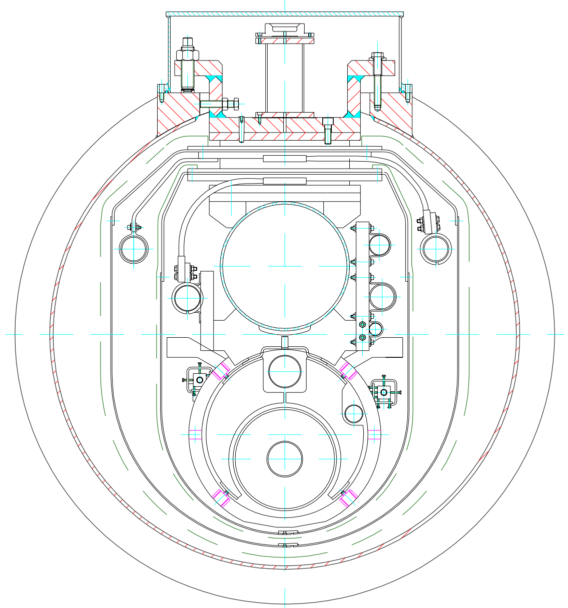


Required plug power for static losses < 5 kW/(12 m module)

Three Generation Cryomodules in TTF

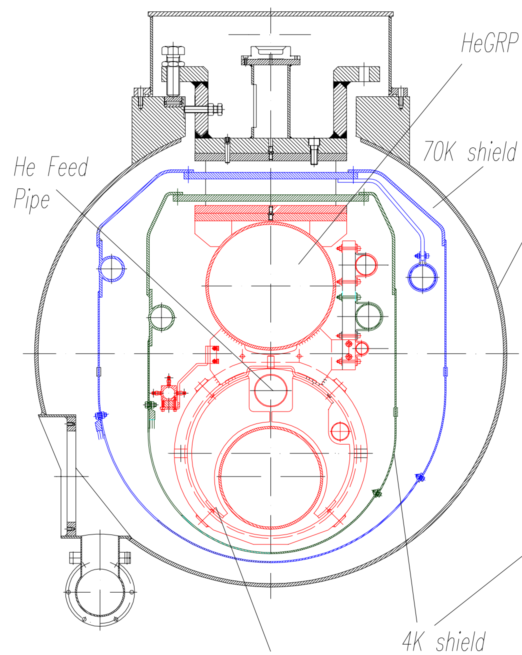


Cry 1



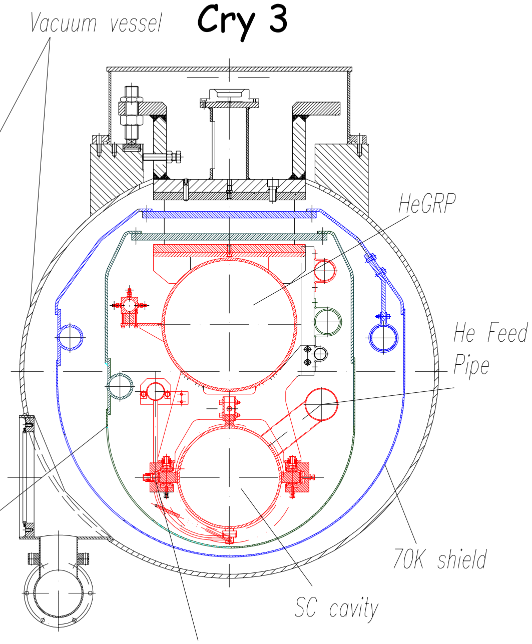
1st Module in TTF I

Cry 2



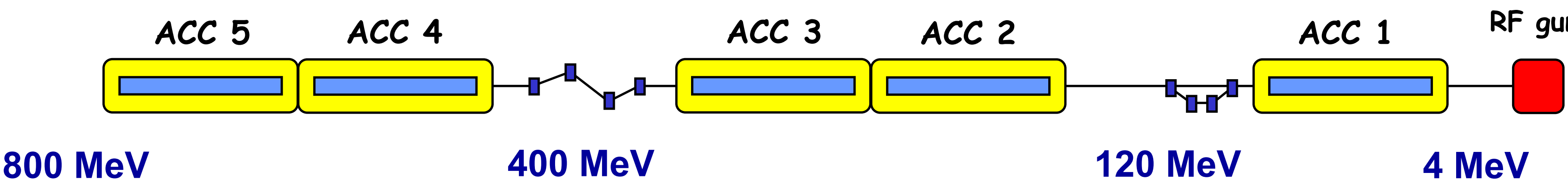
Module 1 & 2 in TTF I
Module 1, 2 & 3 in TTF II

Cry 3



Module 4 & 5 in TTF II

Cryoodules installed in TTF II

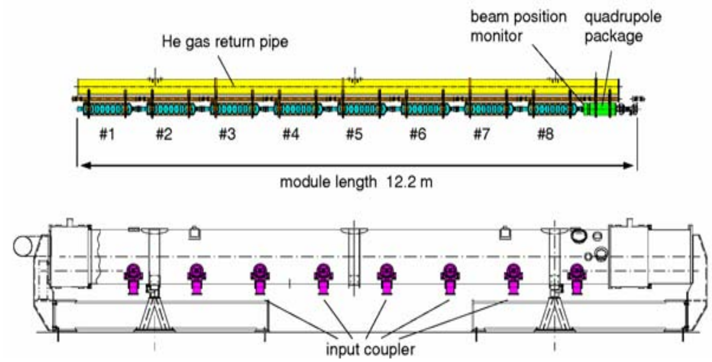


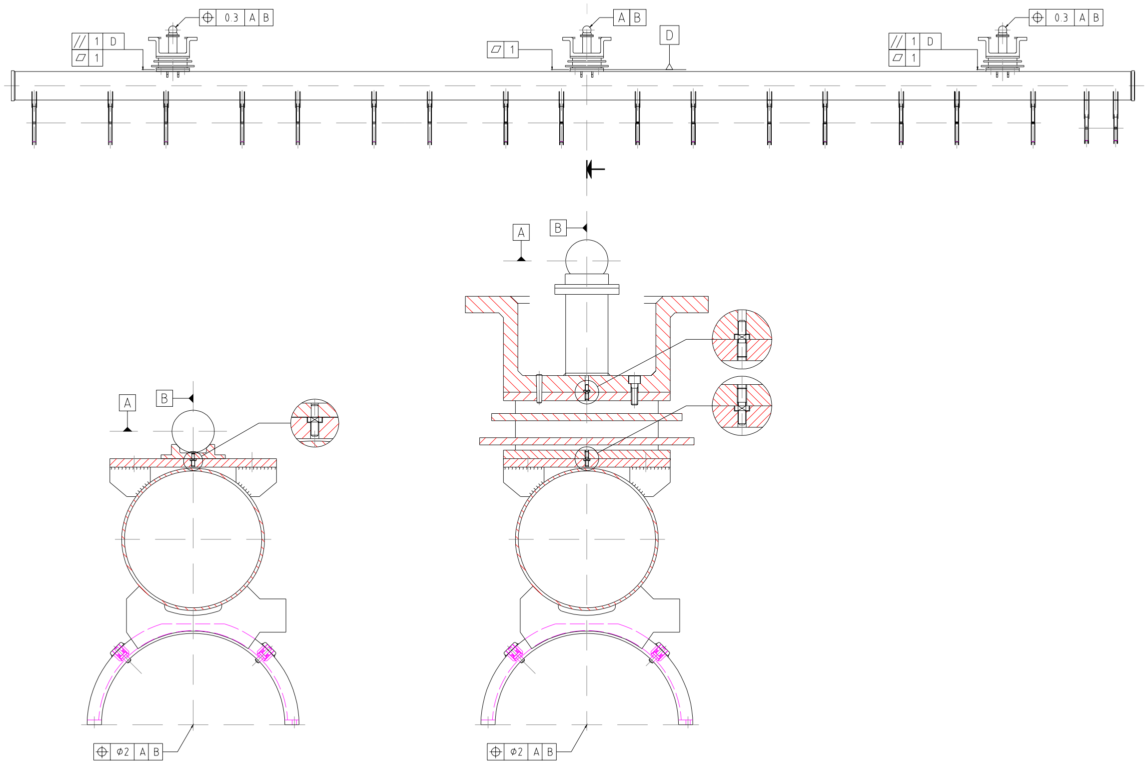
TTF Cryomodule Operation Experience

	Type	Installation date	Cold time [months]
CryoCap		Oct 96	50
M1	1	Mar 97	5
M1 rep.	2	Jan 98	12
M2	2	Sep 98	44
M3	2	Jun 99	35
M1* MSS	2 2	Jun 02	30 8
M3* M4 M5	2 3 3	Apr 03	19 19 19
M2*	2	Feb 04	16

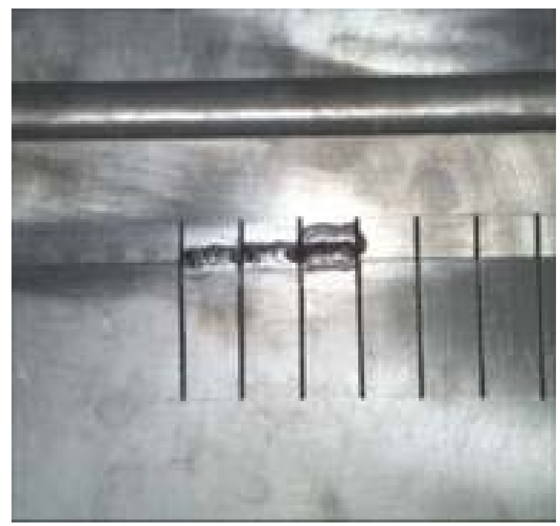
2nd Generation TESLA Cryomodule

- New fabrication sequence
- New strategy for tolerances





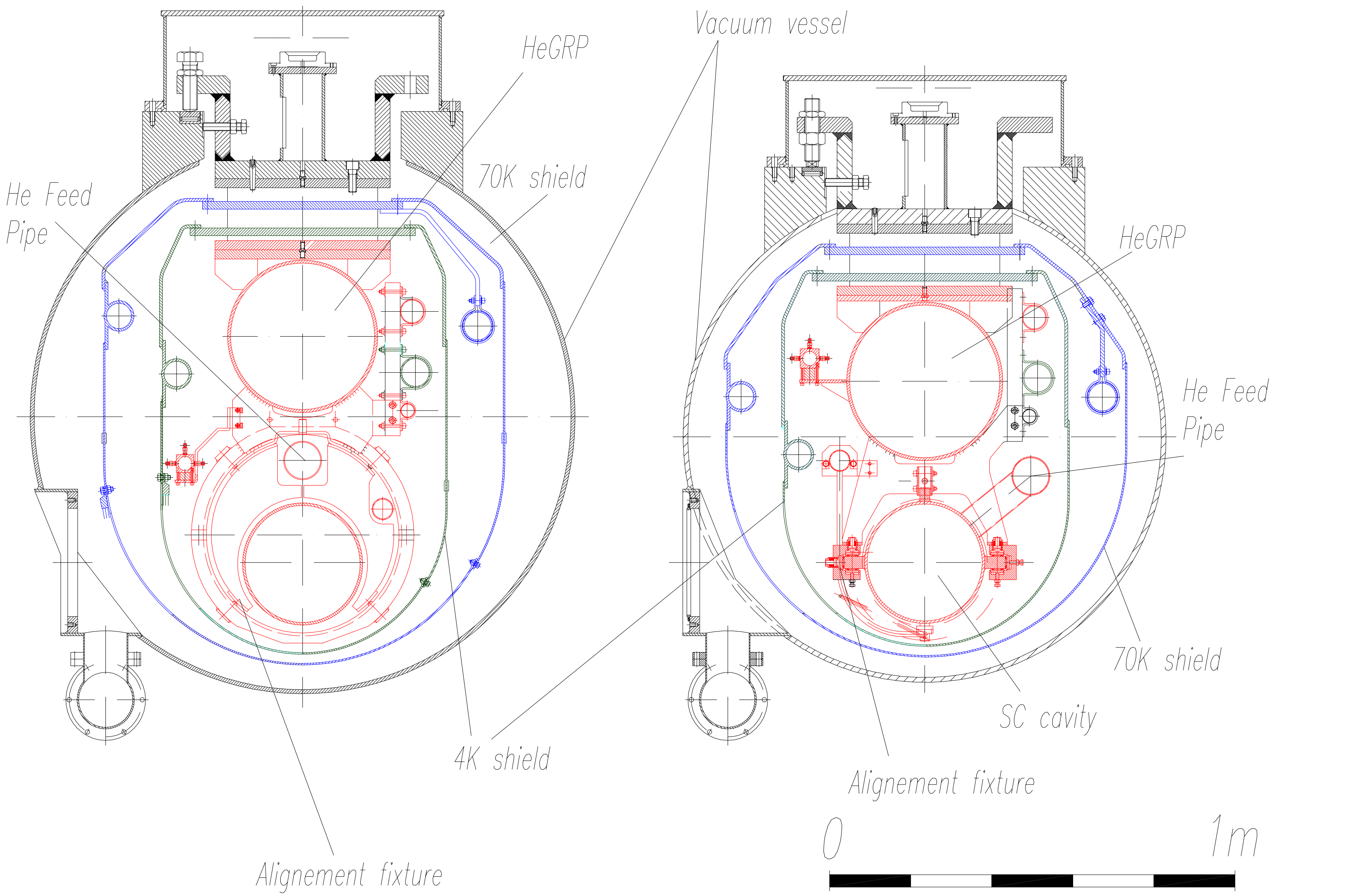
"Finger Welded" Shields



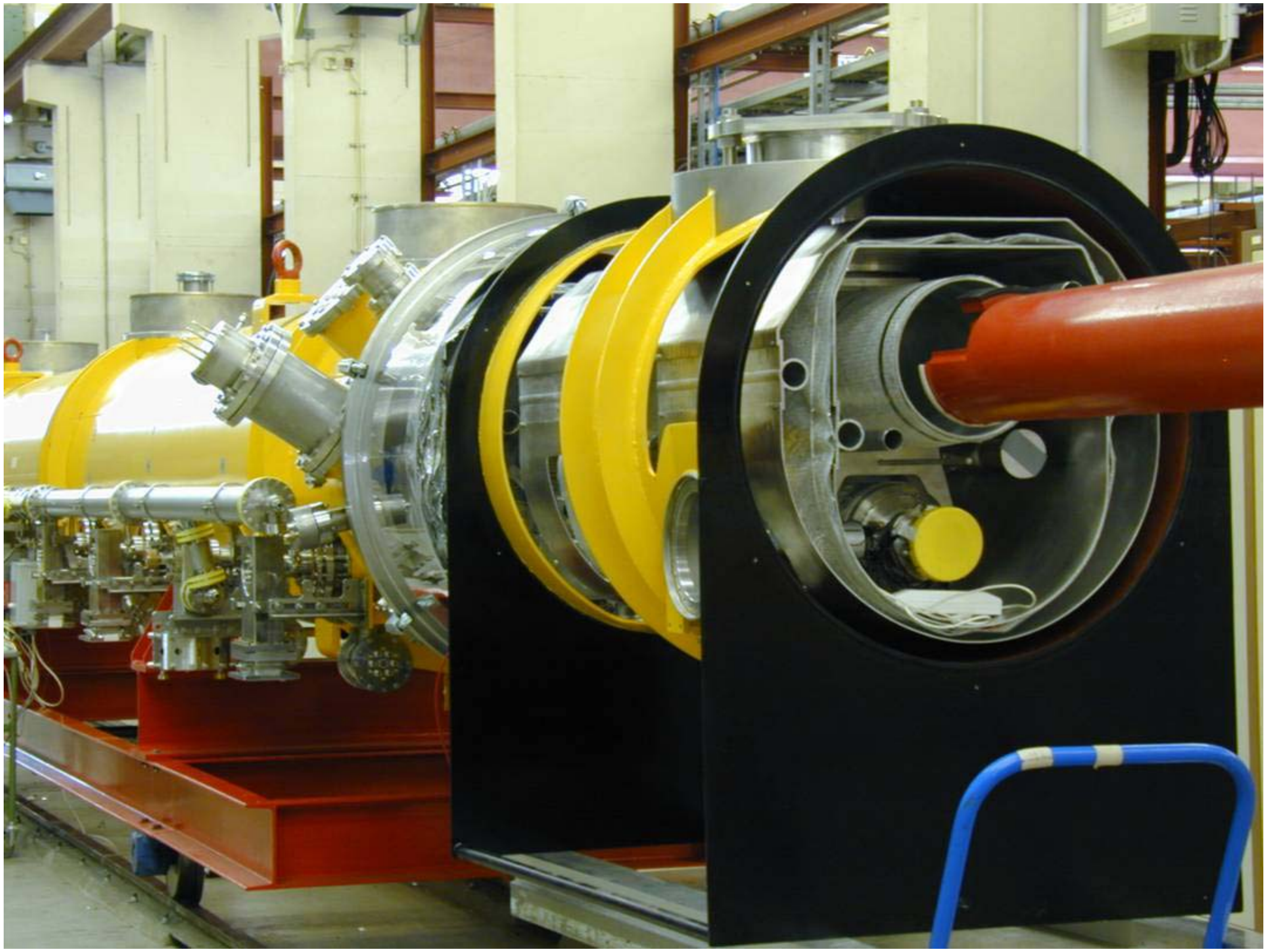
3rd Generation TESLA Cryomodule

- **Reduce the Cross Section and use a standard "pipeline" tube**
  - Redistribute the internal components
  - Reduce the distances to the minimum
- **Improve the connection of the active elements to the HeGRP**
  - Sliding fixtures to allow "Semi Rigid Coupler" and Superstructures
- **Reduce alignment sensitivity to the forces on the HeGRP edges**
  - Move the external posts closer to the edges
  - Include the 300 mm bellow in the in the backbone referencing
- **Further simplify the assembling procedure**
  - Simplify coupler cones and braids
  - Reduce by a factor two the shield components
- **System thought for mass production cost cutting**
  - Tolerances reduced to the strictly required ones
  - Simpler components and standard tubes wherever possible

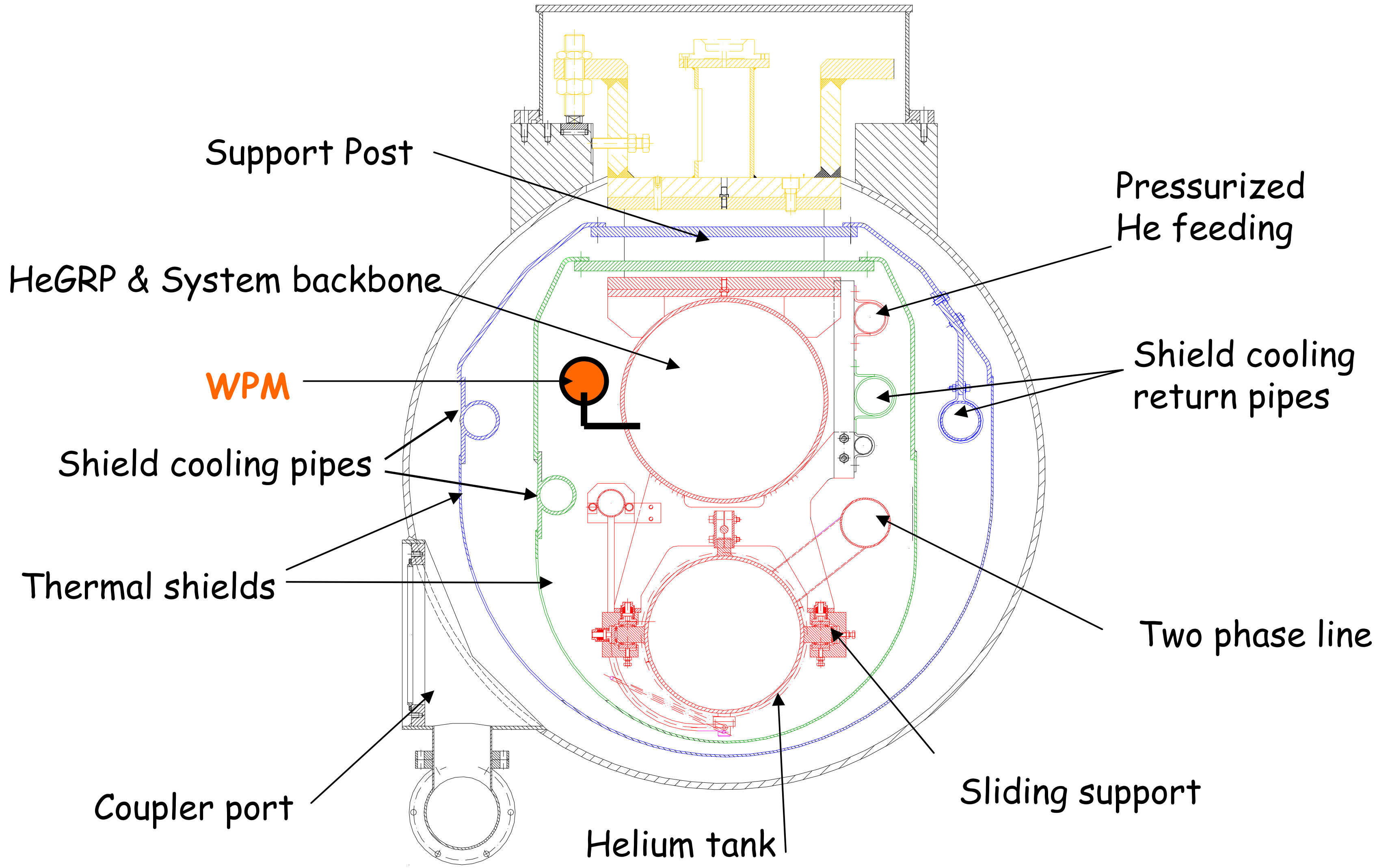
Cry2 & Cry3: Cross Sections



Cry2 to Cry3: Diameter Comparison

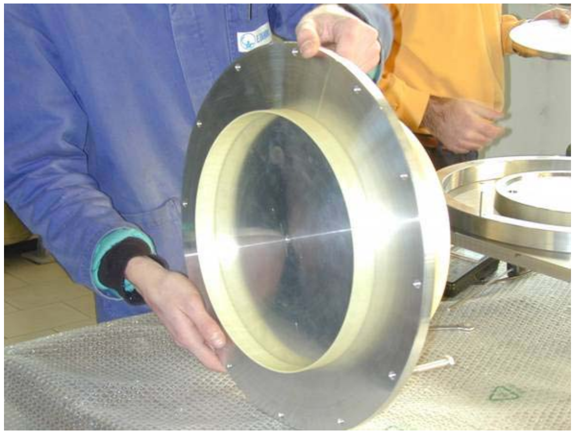


Cry3 Cross Section



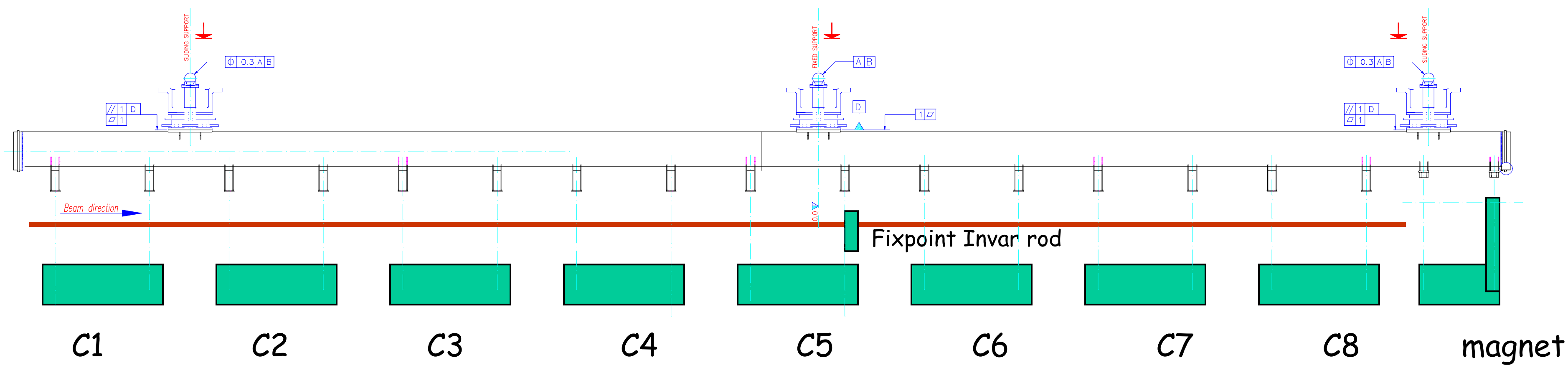
Support Posts

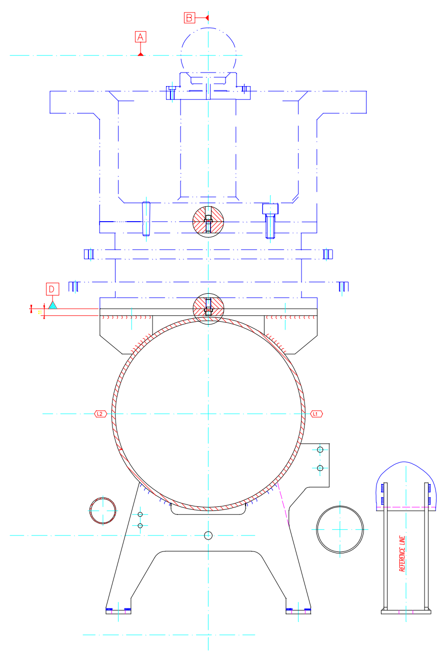
FNAL Design



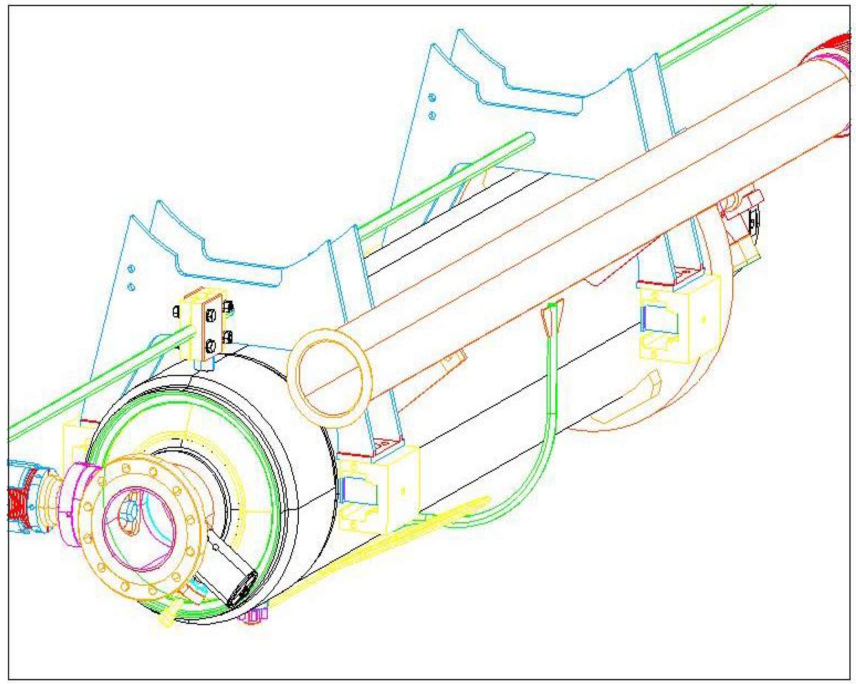
Helium GRP, Posts & Invar Rod

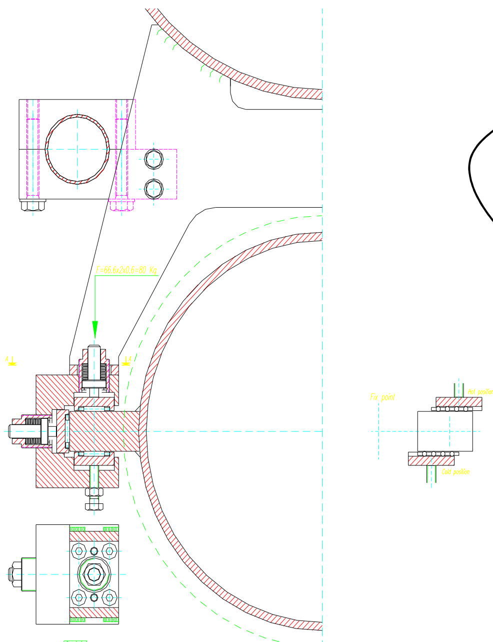




Sliding Fixtures to HeGRP

- Four C-Shaped SS elements clamp a titanium pad welded to the helium tank.
- Rolling needles reduce drastically the longitudinal friction
- Cavities result independent from the elongation and contraction of the HeGRP.
- Lateral and vertical position are defined by reference screws
- Longitudinal position by an Invar Rod

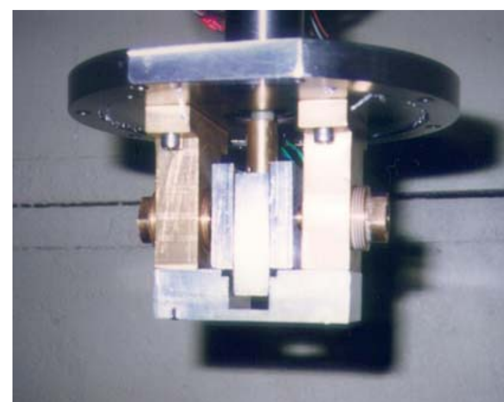




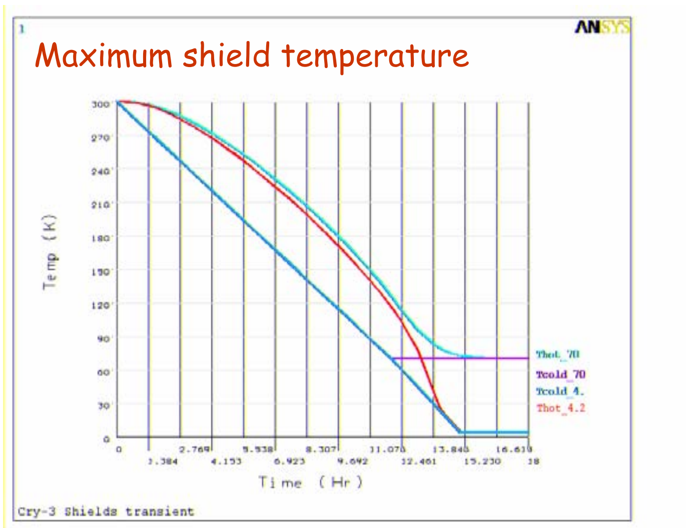
A Moke-up has been built to measure Friction force.

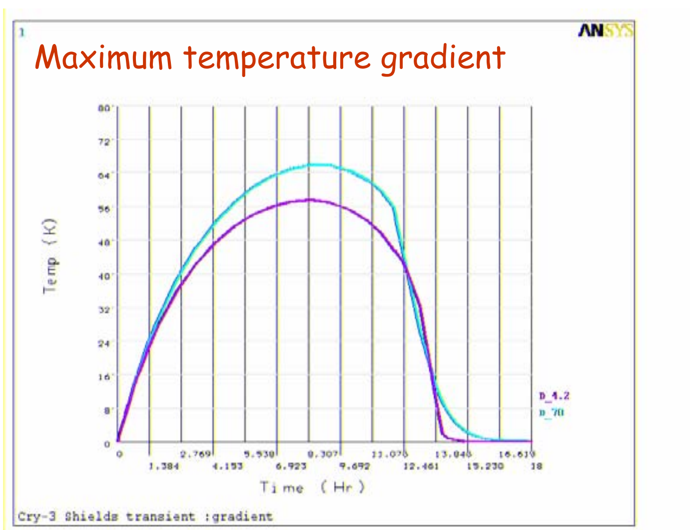
Results presented at CEC-99.

Friction force: 0.1 kgf

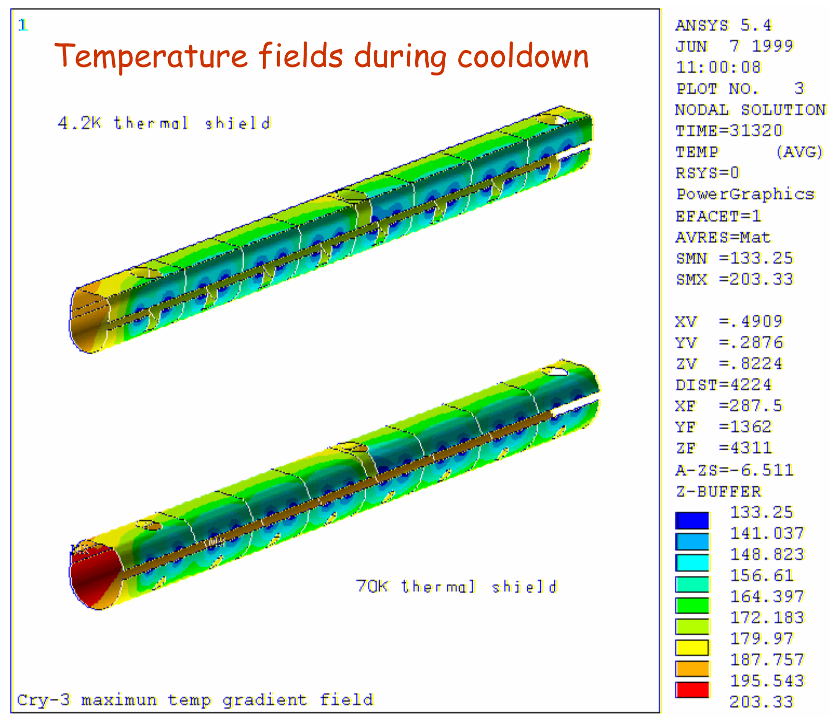


Finger-Welded Shield Behavior





- Cooldown simulation of the 4.2 K and 70 K aluminum thermal shields.
- We used a simultaneous 12 hour linear cooldown.
- The maximal thermal gradient on the shields (upper left graph) is below 60 K, a safe value.
- The temperature fields show that the gradient is concentrated in the welding region, where the fingers unload the structure

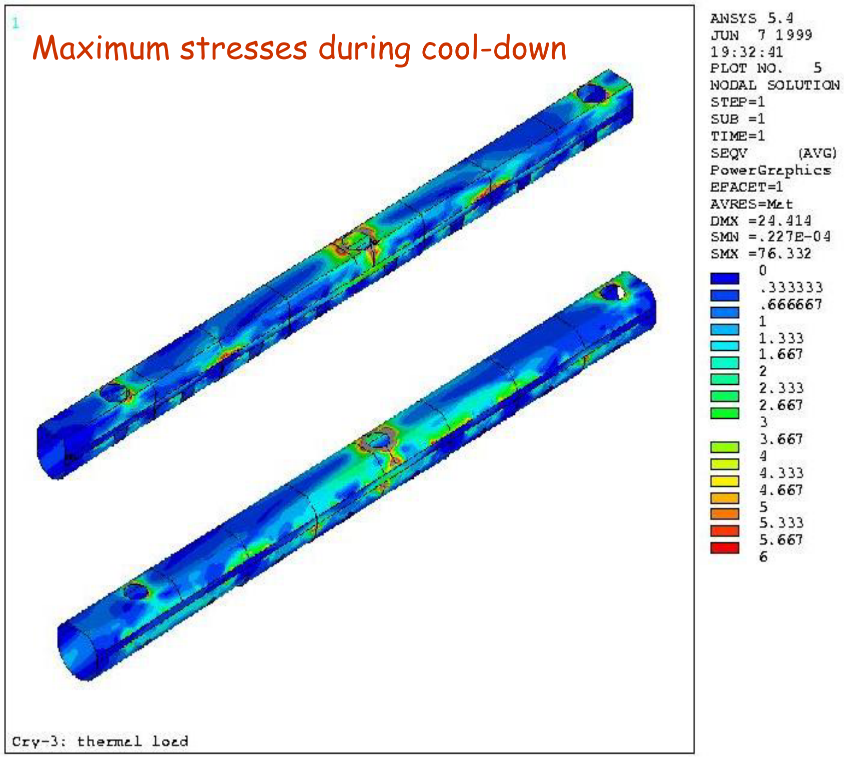


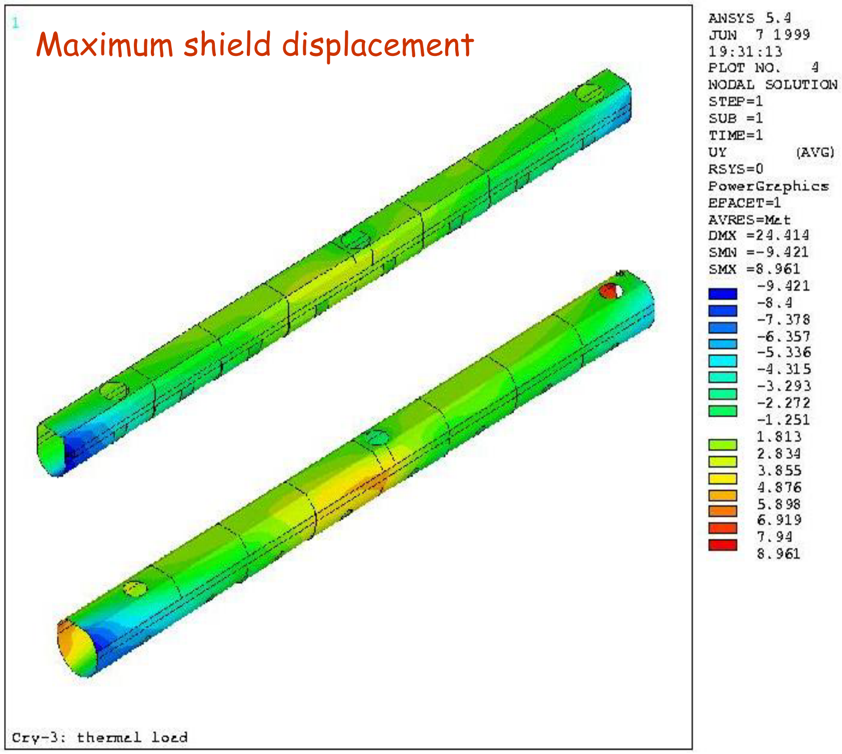
Thermo-mechanical analysis of Shields

Applying the computed temperature field, deformations and stress distribution can be easily computed.

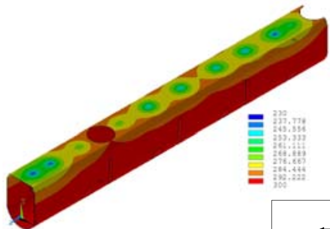
Maximum stresses are within acceptable limits

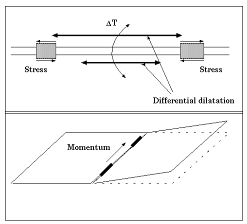
Maximum deformations due to asymmetric cooling are below 10 mm.





From Prototype to Cry 3



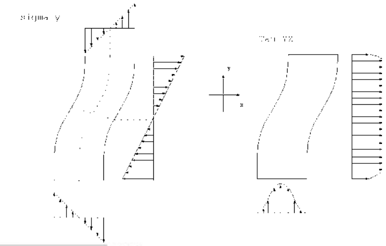


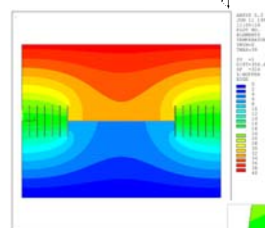
Extensive FEA modeling (ANSYS™) of the entire cryomodule

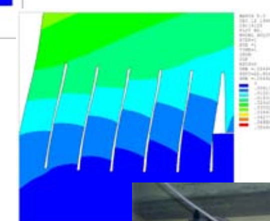
- Transient thermal analysis during cooldown/warmup cycles,
- Coupled structural/thermal simulations
- Full nonlinear material properties

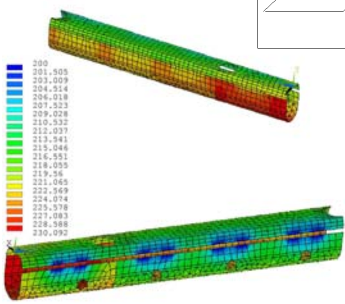
Detailed sub-modeling of new components and Laboratory tests

- Finger-welding tests at ZANON
- Cryogenic tests of the sliding supports at INFN-LASA

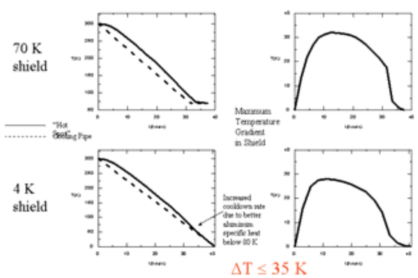


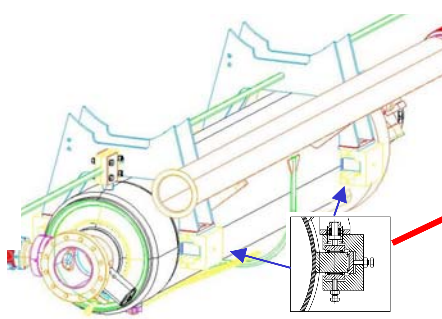


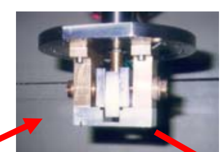




Welded Shields





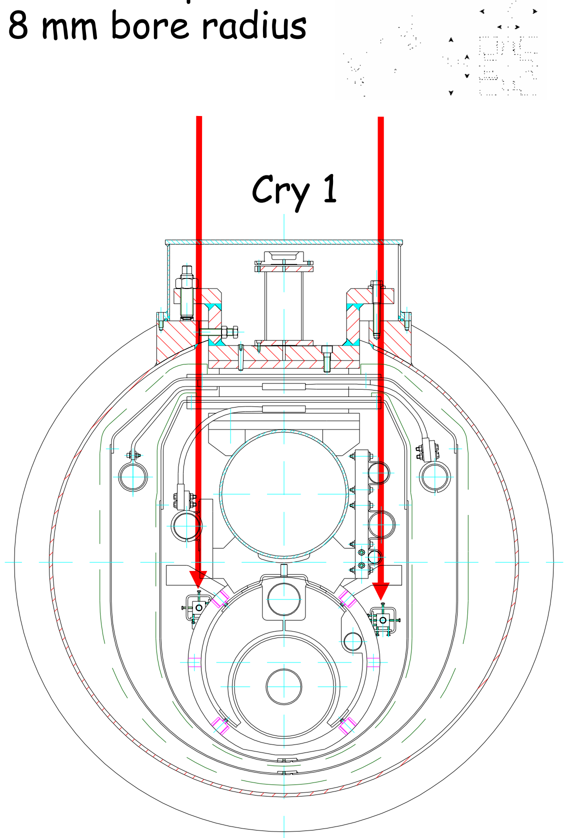


WPMs to qualify alignment strategy

WPM = Wire Position Monitor

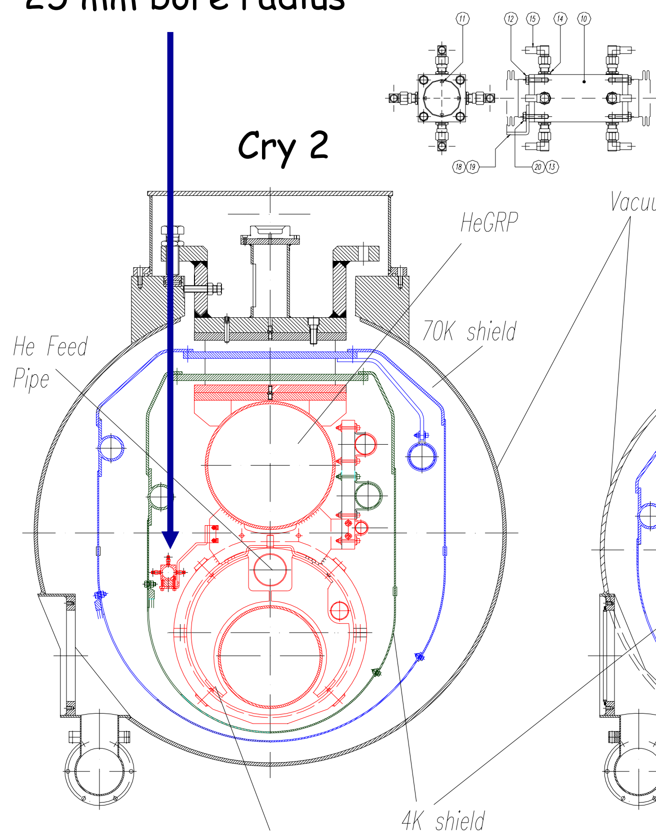
On line monitoring of cold mass movements during cool-down, warm-up and operation

2 WPM lines with 2 x 18 sensors
4 sensors per active element
8 mm bore radius



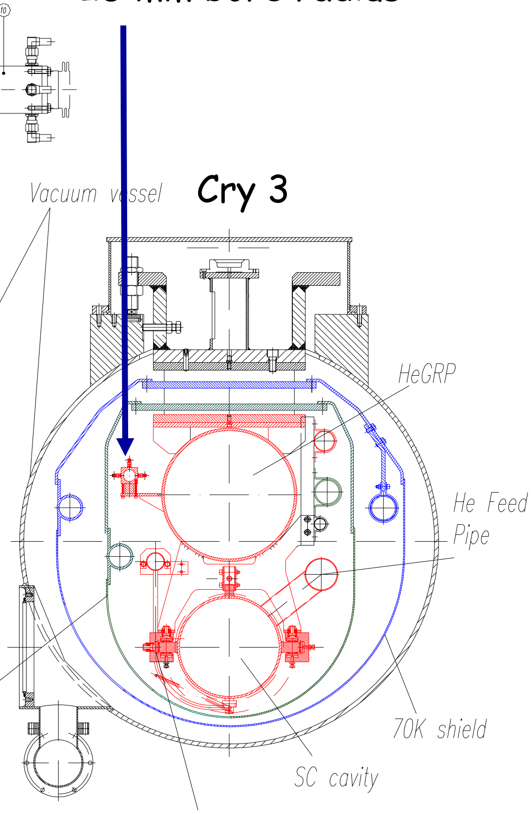
Module 1

1 WPM lines
1 sensors per active element
25 mm bore radius



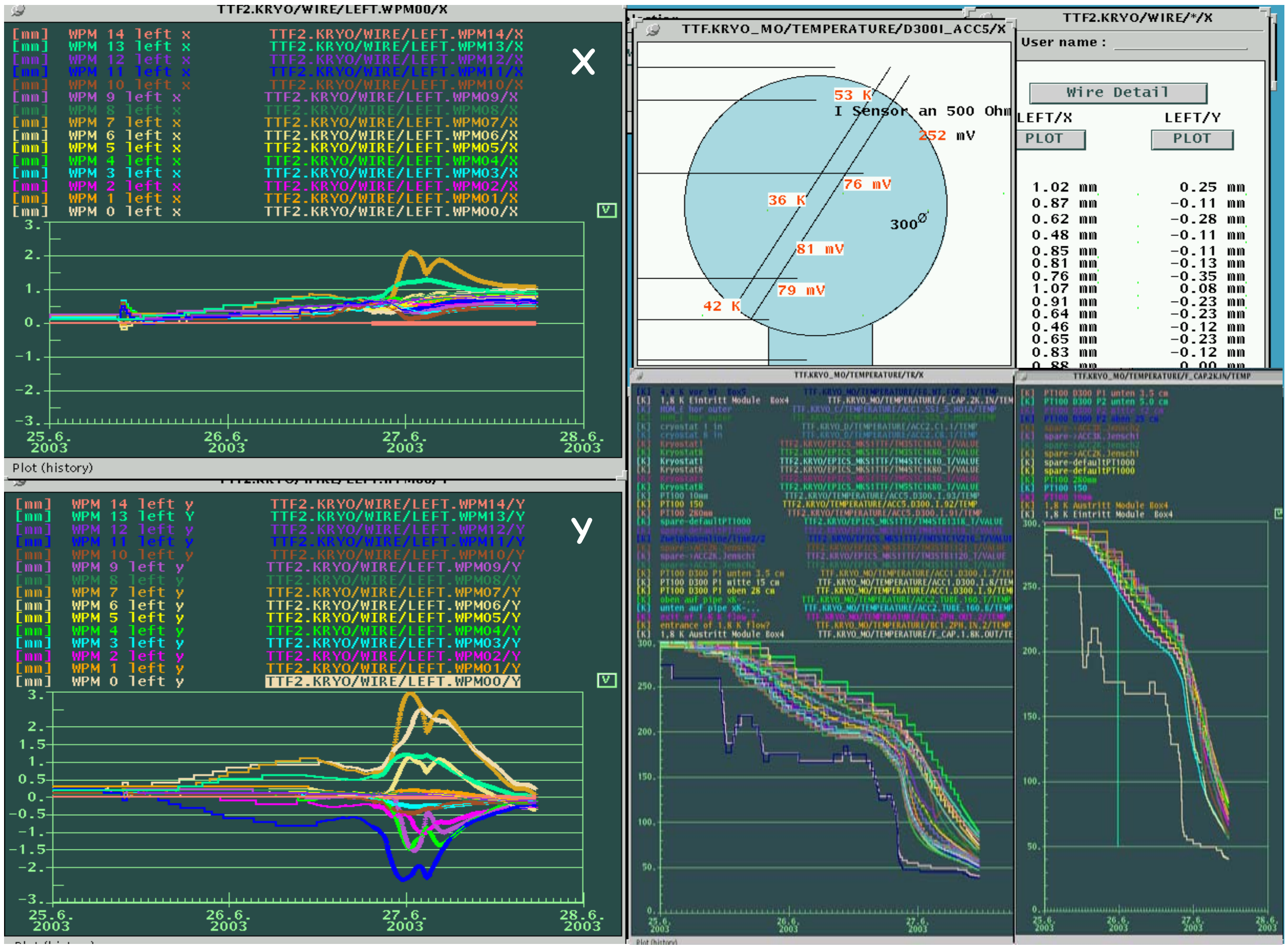
Module 2 & 3

1 WPM line
7 sensors/module
25 mm bore radius



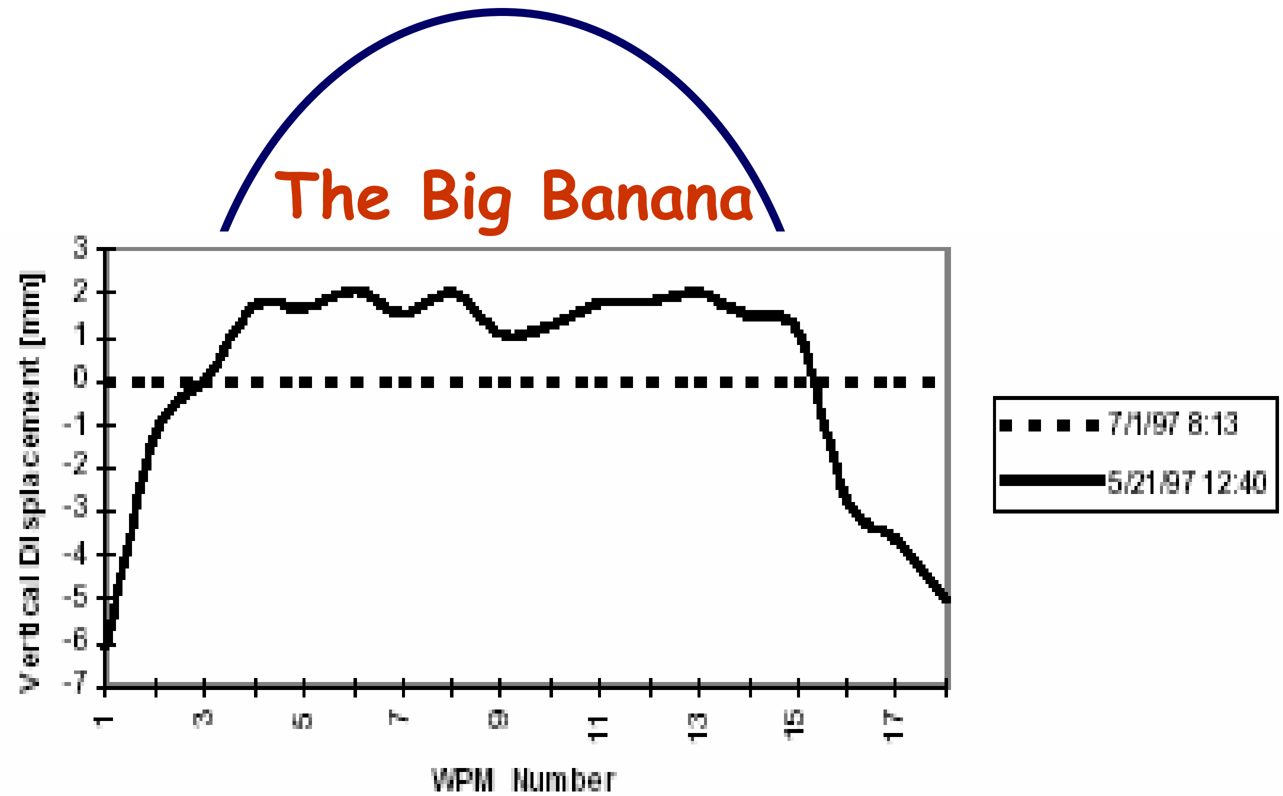
Module 4 & 5

Safe Cooldown of ACC4 and ACC5

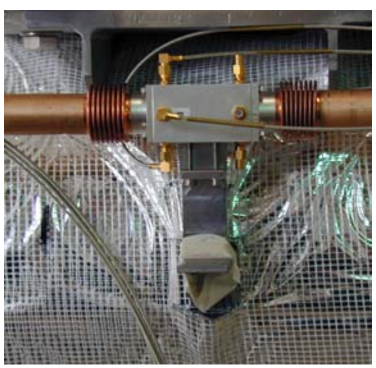


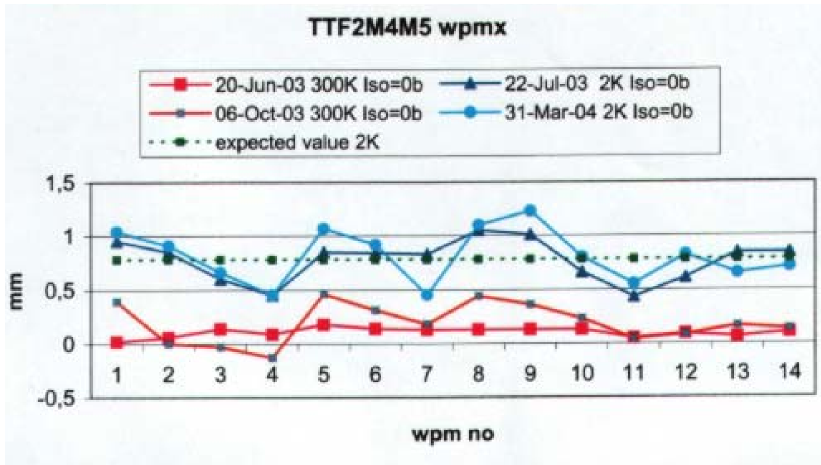
Large Bending in First Cooldown

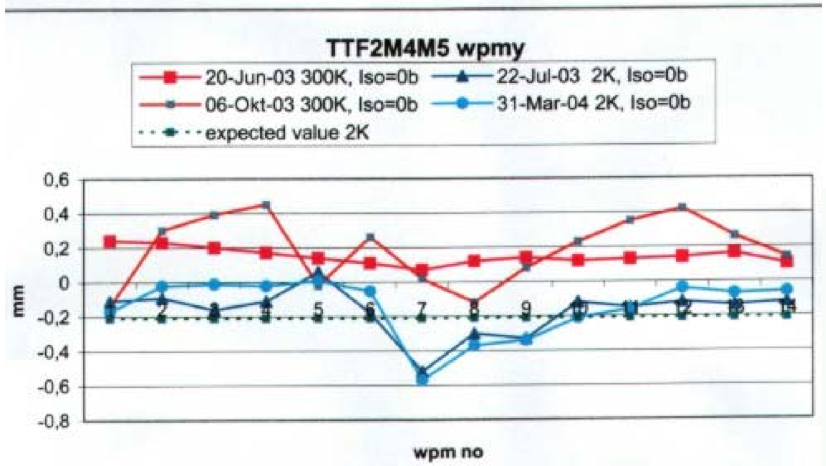
New Cooldown procedure suggested by the WPM's measurements during the first "fast" cooldown



ACC4 & ACC5 Met Specs







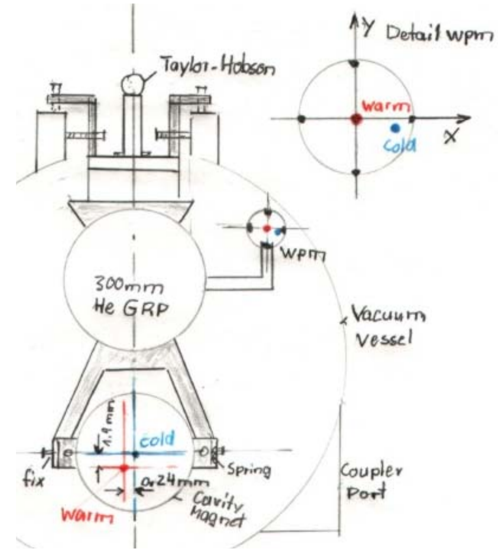
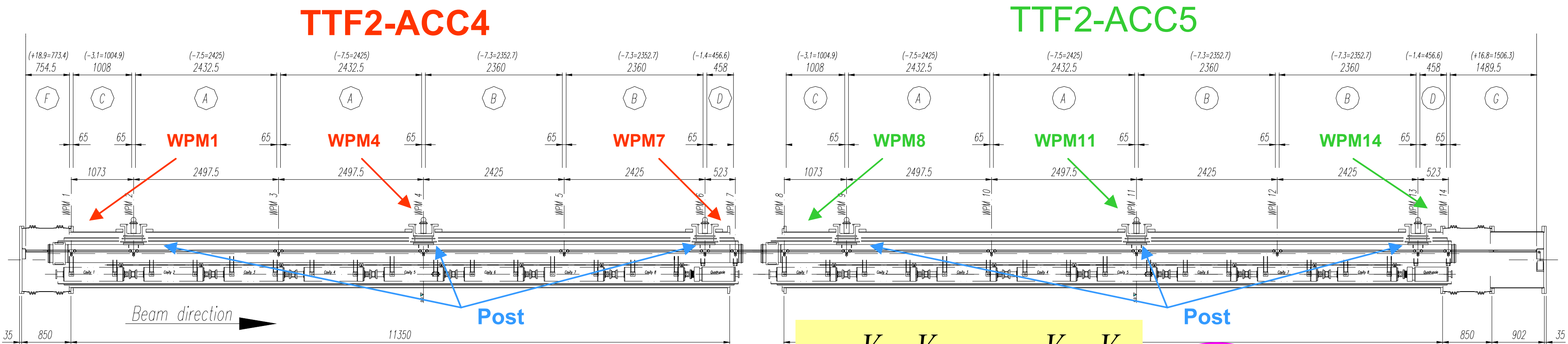


Table 1: Result Summary.

TDR Specifications (rms)		
Cavities	x/y	± 0.5 mm
Quadrupoles	x/y	± 0.3 mm
WPM results (peak)		
Cavities	x	+ 0.35/- 0.27 mm
	y	+ 0.18/- 0.35 mm
Quadrupoles	x	+ 0.2/- 0.1 mm
	y	+ 0.35/- 0.1 mm

- Still some work at the module interconnection
- Cavity axis to be properly defined

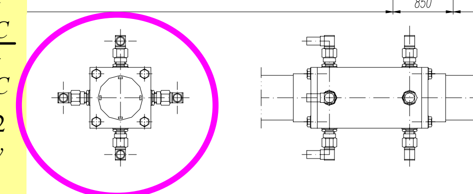
WPM as Vibration Sensors

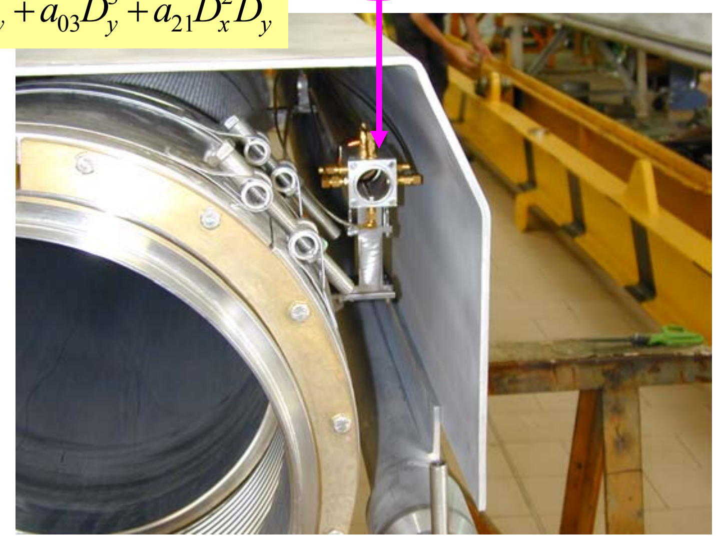


$$D_x = \frac{V_B - V_D}{V_B + V_D} \qquad D_y = \frac{V_A - V_C}{V_A + V_C}$$

$$x = a_{10} D_x + a_{30} D_x^3 + a_{12} D_x D_y^2$$

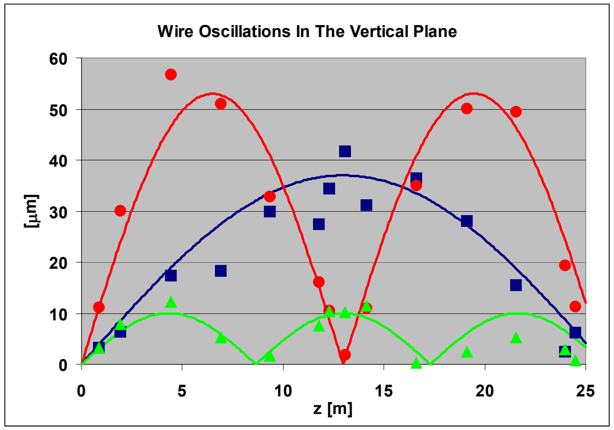
$$y = a_{01} D_y + a_{03} D_y^3 + a_{21} D_x^2 D_y$$

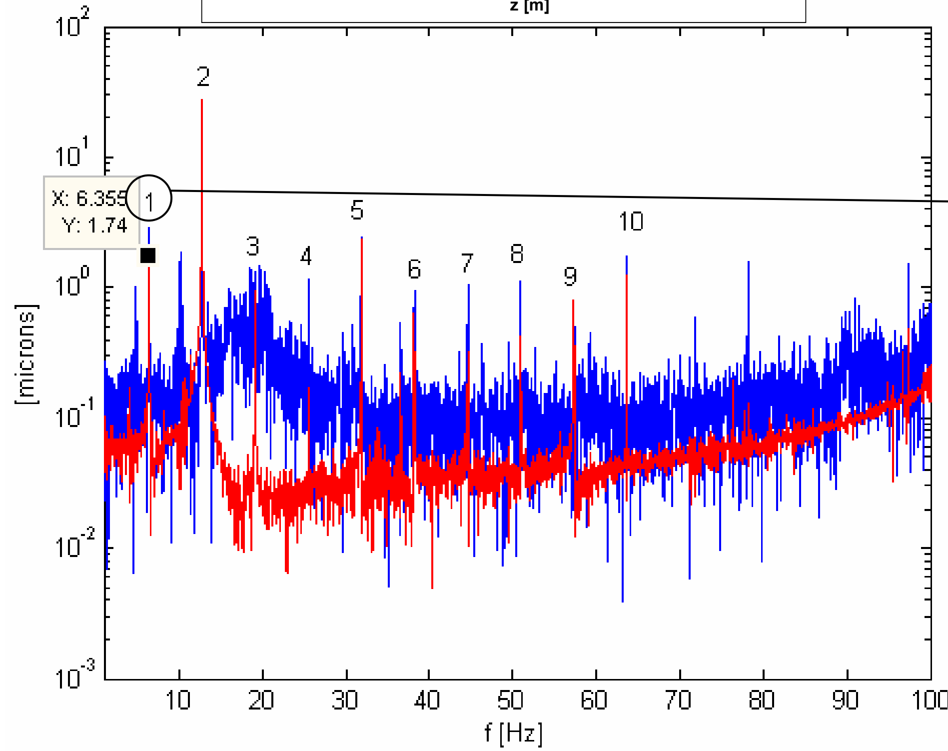




- A WPM is a sort of microstrip four channel directional coupler. A 140 MHz RF signal is applied on a stretched wire placed (nominally) in the center of the monitor bore.
- A Wire Position Monitor (WPM) system has been developed for on-line monitoring of the cold mass during cooldown and operation.
- The low frequency vibrations of the cold mass, amplitude modulate the RF signals picked up by the microstrips.
- The microphonics (and the sub-microphonics) can be recovered de-modulating the microstrip RF signal.

A sample spectrum





- The wire proper vibration spectral lines (fundamental and harmonics) overcome the cold mass mechanical vibration lines.
- On the other hand, being their frequencies well predictable by VSE which completely agrees with the experimental data, it's easy to filter them when processing the data.

Vibrating String Equation (VSE)

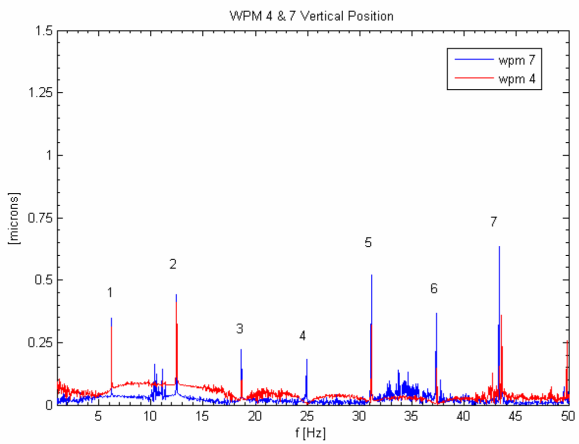
$$f_n = \frac{n}{2\,\ell}\sqrt{\frac{F}{\rho\,A}} = n \cdot 6.4\ \text{Hz}$$

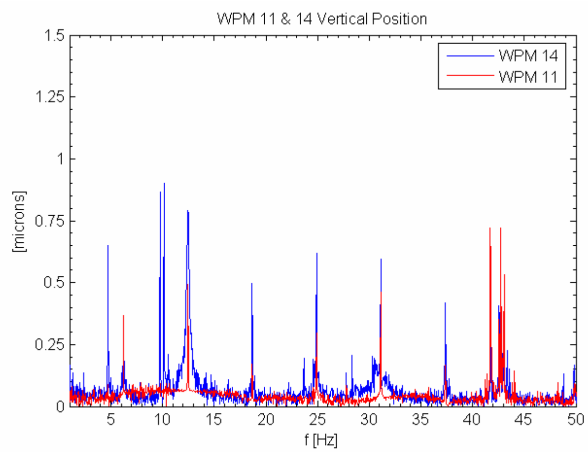
Wire parameters

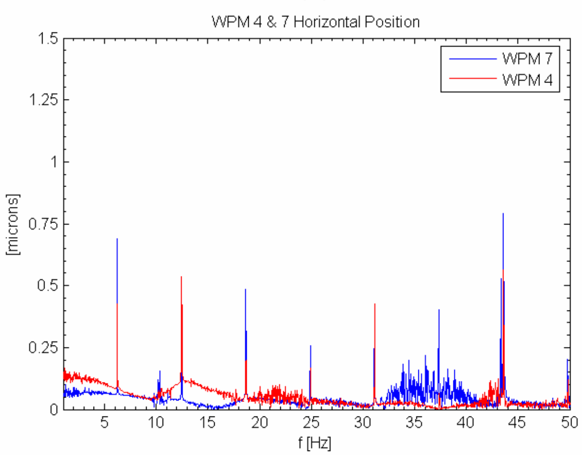
- Wire: (CuBe) (BERYLCO 25)
- Density (ρ): 8.25 g/cm^3 = 8250 kg/m^3
- Cross Section (A): 0.196 mm^2
- Stretched Wire Length (ℓ) 25.950 m
- Tensile Strength: 18 kgp = 176.58 N

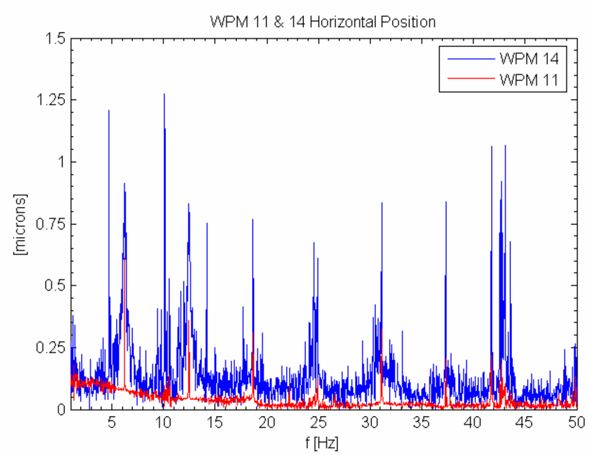
Preliminary Vibration Spectra

WPMs 4 and 11 are close to the central post: cold mass fix point.
WPMs 7 and 14 are at the end of the corresponding cryomodules.









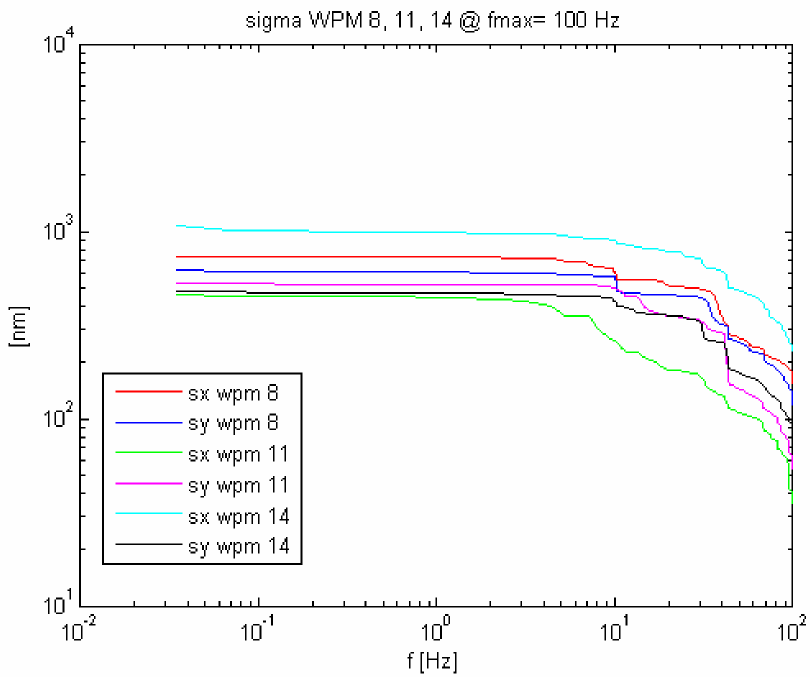
We have preferred to not filter completely the wire oscillation lines to not suppress useful information.

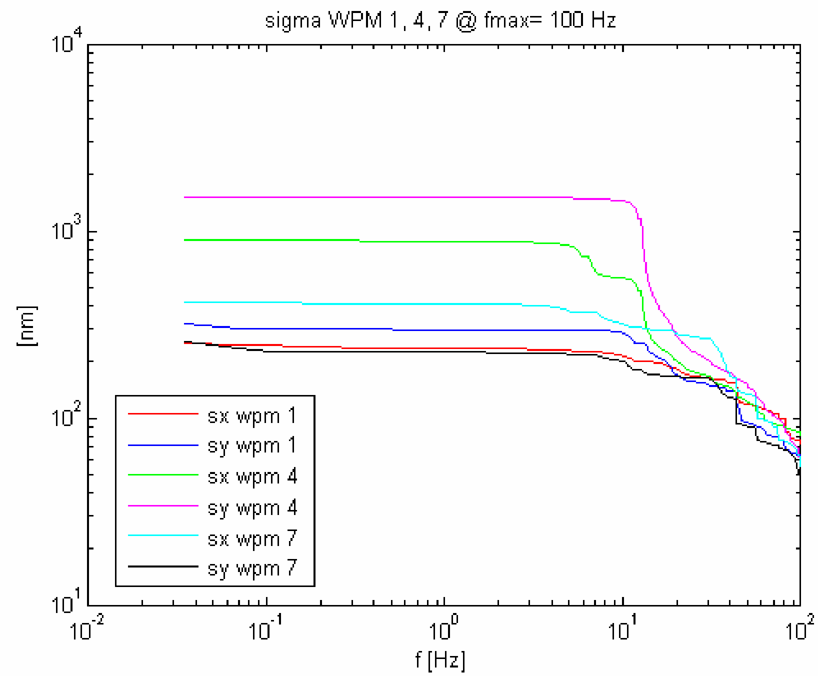
Looking to WPM 14, a significant amount of noise is present between 10 Hz and 30 Hz, 30 Hz and 40 Hz, due to the proximity of vacuum pumps and similar devices, and under 10 Hz, possibly due to the cryogenic system.

On the contrary, the spectra of the WPM 11 signals, which is at the central post position, shows only the harmonics (filtered) of the wire oscillations.

Vibration Variance

- WPM 1 & 8 are at the beginning of the cryomodule 4 & 5 respectively.
- The variances of WPM 4 is dominated by the low frequency noise as shown in the PSD.
- For all the WPMs, a small contribution to the variance comes from the spectral losses of the wire self oscillations lines.
- A more efficient procedure to remove these contributions is under study.

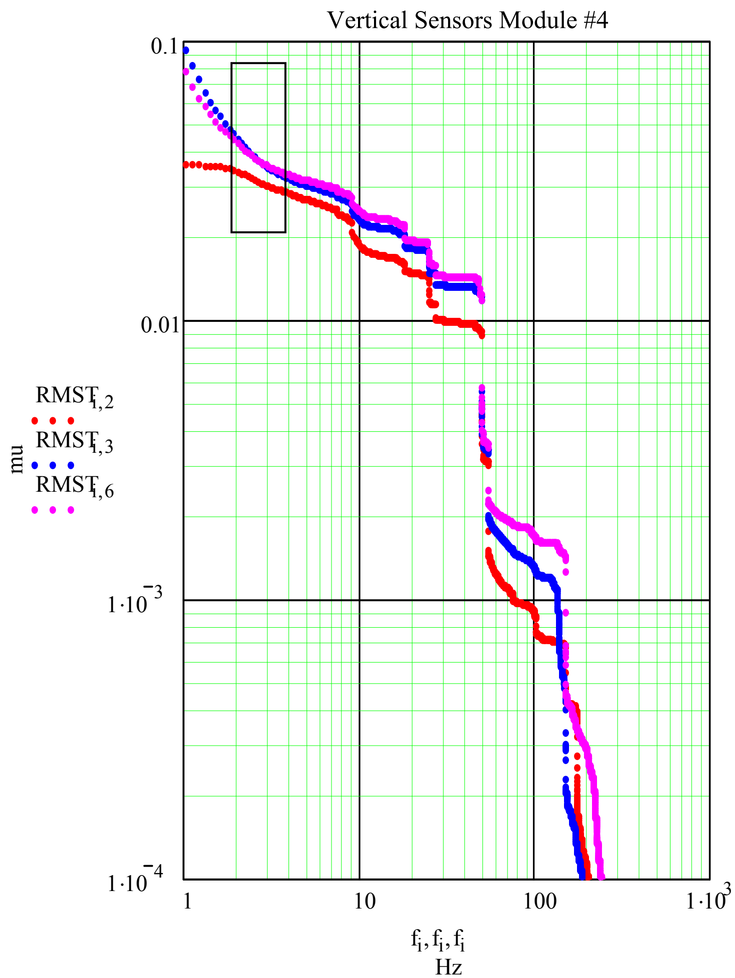




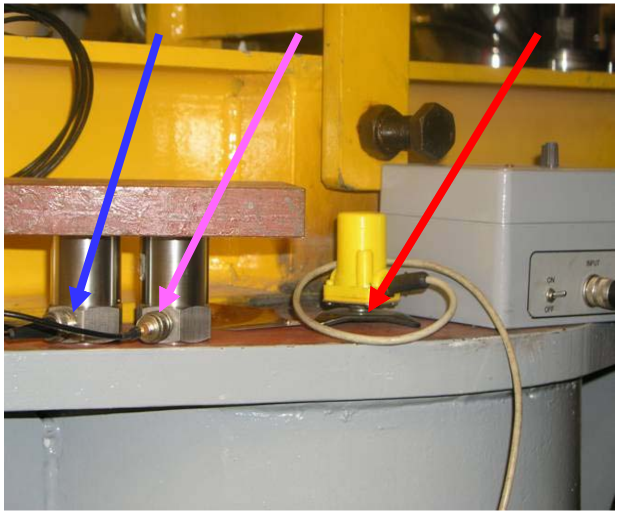
Vibration on quad in module ACC4

(H. Brueck / DESY)

RMS average, Saturday midnight ± 1 hour



Piezo blue and pink, Geophone red



- Good agreement between
  - the two piezos
  - piezo and geophone (20%)
- Low RMS: 34 43 45 nm for f>2Hz
- Comparable with ground motions measured by Ehrlichmann
- At low frequencies the noise signal is probably getting dominant

TTF Module Cold test Overview

Module	Type	Assembly Year	Days	Installation and Test in TTF-Linac		Therm. Cycles cold/warm
Capture	Spec.	Saclay 1996		Oct-96	96-->Sep-03	c/w 13
M1	I	1997	>>	Mar-97	97-->Sep-97	c/w 2
M1 rep.	I	1997/98	>>	Jan-98	98-->Mar-99	c/w 3
M2	II	1998	>>	Sep-98	98-->May-02	c/w 3
M3	II	1999	35+15	Jun-99	99-->May-02	c/w 1
M1*	II	2000	24	Jun-02	02-->	c/w 3 +1
M4	III	2001	18+10	Apr-03	03-->	c/w 1 +1
M5	III	2002	30	Apr-03	03-->	c/w 1 +1
MSS	Spec.	2002	36	Jun-02	02-->Sep-03	c/w 3
M3*	II	2003	18+6	Apr-03	03-->	c/w 1 +1
M2*	II	2004	20	Feb-04	04-->	c/w 1
(M6 EP)	III	(end 2004?)		Modules under test in TTF2-Linac		

Status:15-Sep-04 RLange-MKS-

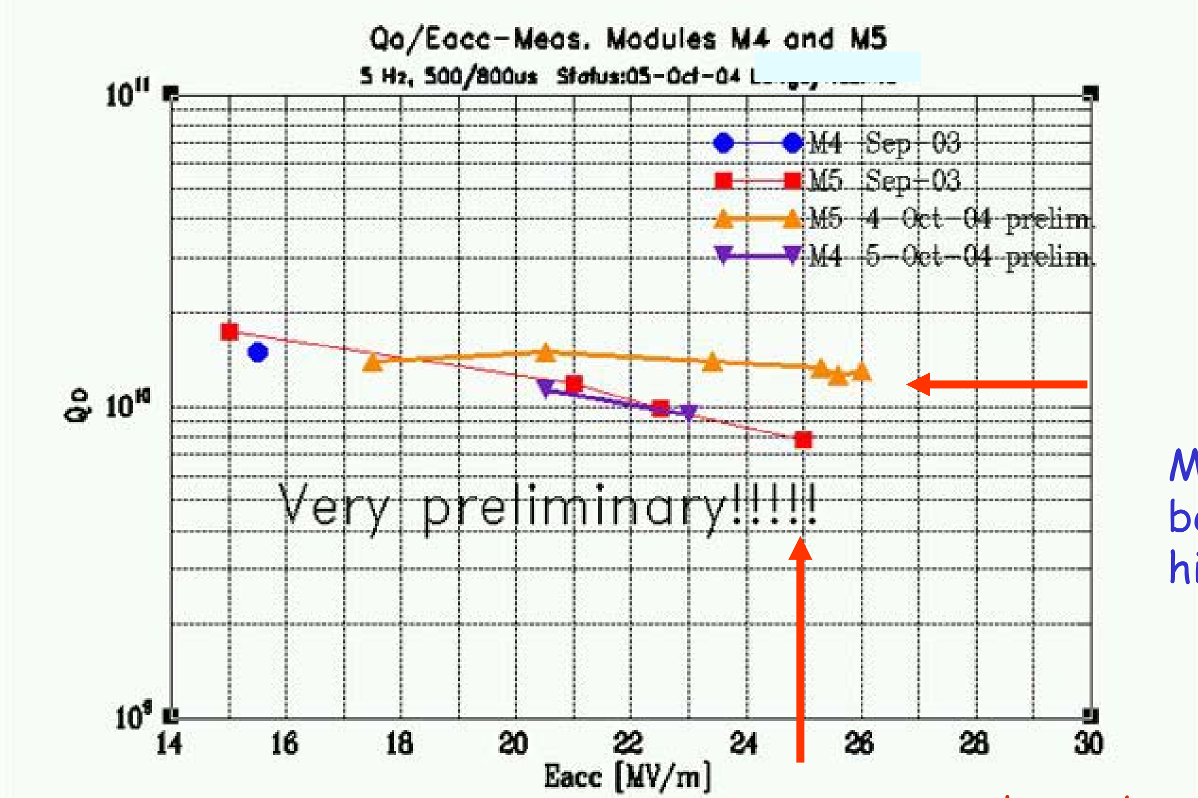
TTF Cryomodule Performances

						Status:15-Sep-04 R.Lange -MKS1-				
Designed, estimated and measured static Cryo-Loads TTF-Modules in TTF-Linac										
Module	40/80 K [W]			4.3K [W]			2 K [W]			Notes
Name/Type	Design	Estim.	Meas.	Design	Estim.	Meas.	Design	Estim.	Meas.	
Capture			46,8			3,9			5,5	Special
Module 1 I	115.0	76.8	90.0 *	21.0	13,9	23.0 *	4,2	2,8	6,0 *	Open holes in isolation
Modul1 rep. I	115.0	76.8	81,5	21.0	13,9	15,9	4,2	2,8	5,0	2 end-caps
Modul 2 II	115.0	76.8	77,9	21.0	13,9	13.0	4,2	2,8	4,0	2 end-caps
Module 3 II	115.0	76.8	72.0 **	21.0	13,9	48.0 **	4,2	2,8	5,0 *	Iso-vac 1E-04 mb, 2e-caps
Module 1* II	115.0	76.8	73.0	21.0	13,9	13.0	4,2	2,8	<3.5	1 end-cap
Module 4 III	115.0	76.8	74	21.0	13,9	13.5	4,2	2,8	<3.5	1 end-cap
Module 5 III	115.0	76.8	74	21.0	13,9	13.0	4,2	2,8	<3.5	1 end-cap
Module SS	115.0	~76.8	72.0	~21.0	~13.9	12.0	~4.2	>2,8	4,5	Special, 2 end-caps
Module 3* II	115.0	76.8	75	21.0	13,9	14	4,2	2,8	<3.5	1 end-cap
Module 2* II	115.0	76.8	74	21.0	13,9	14,5	4,2	2,8	<4,5	2 end-caps
Module 6 EP	Type III, EP-Cavities Goal:Solution close to XFEL Modules									(Assembly End-04??)
	Design and estimated values by Tom Petersen 1995 -Fermilab-							Modules under Test in TTF2-Linac		

TTF Cryomodule Dynamic Losses

2K Dynamic heat losses of module 4 & 5 (type III) : about 3 W at 25 MV/m each

5 Hz, 500/800 µs

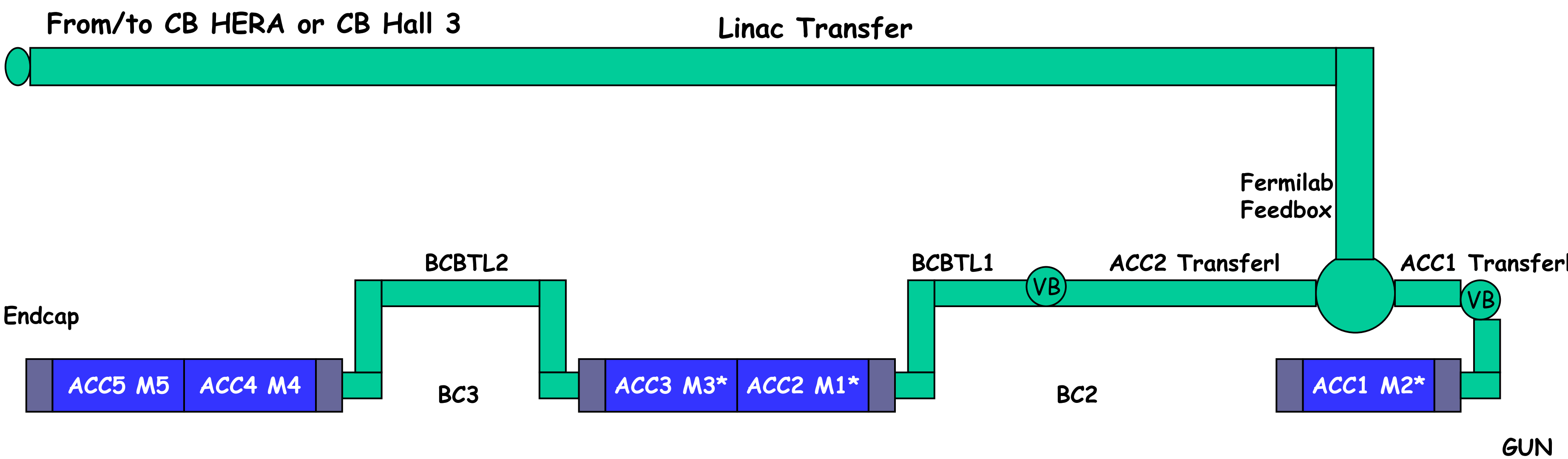


0.38 W/cavity

Most cavities can be operated at higher gradients !

corresponds to about 3 W each

TTF2 Cryogenics since March 2004



Overview:

21-Mar-04	Start of cool down
28-Mar-04	4.3K/1.1bar
29-Mar-04	2 K / 31mbar
07-Jun-04	Linac shut down, cavities kept cold (4.3K/1.1bar)
01-Sep-04	Start of TTF2 Commissioning

Static Cryo losses [Watt]:

	Total	/Module
40/80K	1300	74
4.3K	320+1.6g/s	13
2.0K	21	<3.5

Cold Leaks Experience at TTF

Summary of Vacuum/He Leaks after Cold Tests in TTF/TTF2-Modules

Status:15-Sep-04 R. Lange -MKS-

Module	M1	M2	M3	MSS	M1*	M3*	M4	M5	M2*
Number of leaks Vac	1	6	7	0	1	1	0	0	
Number of cool/warm	3	3	1	3	3 +1	1 +1	1 +1	1 +1	1
He-->insulation	0	0	1 C5 tank weld	0	0	0	0	0	0
			1 C8 bellow w						
Insulation-->coupler	0	0	0	0	0	0	0	0	?
Insulation-->beam pipe	Cav-flange	4 BPM feed-thr	1 BPM feed-th	0	1	1(more?)	0	0	?
		1 C6 e-pickup	2 C2/C8 e-pick						
			1 C7 coup-flan						
Coupler-->beam pipe	0	1 C1 ceram wi		0	0	0	0	0	?
He-->beam pipe	0	0		0	0	0	0	0	0

A Few Comments on Cry 3 Cryomodule

Proven design, just few details to clean up

- Most are useful, but not necessary, for X-FEL
- Ongoing Industrialization for X-FEL good for ILC too

A few examples of foreseen improvements:

- Quad Fixture (sliding as for cavities) – planned for X-FEL
- Flange connections: Sealing and Fixing
- Various braids for heat sinking (all coupler sinking stile)
- Cables, Cabling, Connectors and Feed-through
- Composite post diameter (and fixture for transportation)
- Warm fixtures of cold mass on Vacuum Vessel (fixed and sliding)
- LMI Blankets for the 50-70 K shield (LHC Style)
- Module interconnection: Vacuum Vessel sealing, pipe welds, etc.
- Coupler provisional fixtures and assembly

TESLA Cryomodule Concept Peculiarities

Positive

- Very low static losses
- Very good filling factor: Best real estate gradient
- Low cost per meter in term both of fabrication and assembly

Project Dependent

- Long cavity strings, few warm to cold transitions
- Large gas return pipe inside the cryomodule
- Cavities and Quads position settable at ± 300 μm (rms)
- Reliability and redundancy for long MTTR (mean time to repair)
- Lateral access and cold window natural for the coupler

Constraints

- Long MTTR in case of non scheduled repair
- Moderate (± 1 mm) coupler flexibility required

Design changes important for ILC

- Move quadrupole to the center
  - Quad/BPM Fiducialization
  - High pressure rinsing and clean room assembly issues
  - Movers for beam based alignment? Why not if really beneficial
- Short cavity design
  - Cutoff tubes length by e.m. not ancillaries (coaxial tuner)
- Cavity inter-connection: Flanges and bellows (coating?)
  - Fast locking system for space and reliability (CARE activity)
  - Bellow waves according to demonstrated tolerances
- Coaxial Tuner with integrated piezo-actuators
  - Parametric "Blade Tuner" or equivalent for real estate gradient
  - Integration of fast tuner (piezo actuated) underway
- Longer module design: 10-12 cavities
  - Length to be based on the overall machine cost optimization

From TTF to ILC

- TTF Operation Experience shows that Cry 3 Modules are close to the optimum in term of performances
- Improvements where conceived at the time of the TESLA TDR, but never developed because of sake of funding and personnel
- X-FEL will use the present design with minimum modifications
- ILC should use the TESLA TDR cryomodule design, very close to the so called Cry 3, as the basis for further improvements
- A review of the Cry3 design for SMTF should be the next step.

LCH and TESLA Cryomodule Comparison